

Rotating Radio Transients: X-ray observations

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Abstract.

Rotating Radio Transients are a new class of neutron stars discovered through the emission of radio bursts. Eleven sources are known up to now, but population studies predict these objects to be more numerous than the normal radio pulsar population. Multiwavelength observations of these peculiar objects are in progress to disentangle their spectral energy distribution, and then study in detail their nature. In this review I report on the current state of the art on these objects, and in particular on the results of new X-ray observations.

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INTRODUCTION

A new class of neutron stars displaying bursting behavior in the radio band (RRATs, aka Rotating Radio Transients) was recently discovered (McLaughlin et al. 2006). These sources are all in the disk of the Milky Way and are characterized by dispersed radio bursts with flux densities (at a wavelength of 20 cm) ranging from 100 mJy to 4 Jy, durations from 2 and 30 ms, and average intervals between repetition from 4 minutes to 3 hours. Through a greatest common denominator study of the arrival times of the bursts, periodicities for all of the RRATs have been discovered. Furthermore, for the most prolific bursters (RRAT 1819–1458, RRAT 1317–5759, and RRAT 1913+1333), also period derivatives (\dot{P}) and accurate positions ($< a$ few arcseconds) have been measured. The timing solution derived from the radio bursts, and their periods and period derivatives ranging from 0.4–7 s and $10\text{--}14 \times 10^{-12} \beta$, respectively, indicate that they are isolated neutron stars (NS). Nevertheless, the properties of their emission are quite different from those of known isolated NSs, such as e.g. radio pulsars (Lorimer & Kramer 2005), magnetars (Woods & Thompson 2006), or X-ray dim isolated NSs (XDINS; van Kerkwijk & Kaplan 2007).

Determining the nature of the emission from these objects, as well as estimating how many RRATs are present in our Galaxy is of paramount importance. The small duty cycle of the radio bursts (0.1–1 s of radio emission per day) makes the discovery of these sources rather difficult, implying that there must be a large population of such objects in the Galaxy. A detailed calculation shows that there may be at least 5–10 times more objects of this class than canonical rotational powered radio pulsars (McLaughlin et al. 2006; Lorimer et al. in prep.). Popov et al. (2006) show that the inferred birthrate of RRATs is consistent with that of XDINS but not with magnetars.

There have been several suggestions put forward on the nature of this new class of NSs. RRATs’ radio bursting behaviour might be similar to the giant pulses sometimes

TABLE 1. Observed and derived parameters for RRAT J1819-1458, RRAT 1317-5759, and RRAT 1913+1333 (radio timing properties derived from McLaughlin et al. 2006). “S” is the flux density at 1.4 GHz, and the X-ray luminosity is unabsorbed in the 0.3–5keV band (see text).

RRAT	Distance (kpc)	P (s)	Age (Myr)	B-field (Gauss)	\dot{E} (erg s ⁻¹)	S (Jy)	X-ray Lum. (erg s ⁻¹)
1819-1458	3.6	4.26	0.117	5.0×10^{13}	2.4×10^{32}	3.6	3.9×10^{33}
1317-5759	3.2	2.64	3.33	5.8×10^{12}	0.3×10^{32}	1.1	$< 7.5 \times 10^{32}$
1913+1333	5.7	0.92	1.86	2.7×10^{12}	3.9×10^{32}	0.6	$< 9.4 \times 10^{34}$

observed in young radio pulsars, or to “nulling” phenomena observed as a turning on and off of the pulsations. However, should be noted that the RRATs with a measured \dot{P} , do not have high inferred values of magnetic field strength at the light cylinder, implying that their emission mechanism is different from that responsible for the “giant pulses” observed from some pulsars (e.g. Knight et al. 2006). Furthermore, unlike most nulling pulsars (e.g. Wang et al. 2007), we typically do not see more than one pulse from the RRATs in succession (although with some exceptions: McLaughlin et al. in prep.). Zhang et al. (2006) suggest that the RRATs may be neutron stars near the radio “death line”, however, the period derivatives measured for three RRATs do not place them near canonical pulsar “death lines” (e.g. Chen & Ruderman 1993). Another intriguing possibility is that the sporadicity of the RRATs is due to the presence of a circumstellar asteroid belt (Cordes & Shannon 2006; Li 2006) or a radiation belt such as seen in planetary magnetospheres (Luo & Melrose 2007). Or, perhaps, they are transient X-ray magnetars, a particularly relevant suggestion given the recent detection by Camilo et al. (2006) of transient radio pulsations from the anomalous X-ray pulsar XTE J1810-197. A final possibility is that they are similar objects to PSR B0656+14, one of three middle-aged pulsars (i.e. “The Three Musketeers”; Becker & Truemper 1997) from which pulsed high-energy emission has been detected (e.g. DeLuca et al. 2005). Weltevrede et al. (2006) convincingly show that if PSR B0656+14 were more distant its emission properties would appear similar to those of the RRATs.

X-RAY OBSERVATIONS

RRAT J1819-1458

RRAT J1819-1458 is one of the most prolific radio bursters, and shows the brightest radio bursts of any of the RRAT sources (see Tab. 1 for details on this source). Thanks to a serendipitous *Chandra* observation, we detected X-ray emission from this source in a 30 ks ACIS-I observation toward the (unrelated) Galactic supernova remnant G15.9+0.2 (Reynolds et al. 2006). The spectrum was described by an absorbed blackbody, but the timing resolution was not sufficient to allow a robust search for X-ray pulsations. We then re-observed the source with *XMM-Newton* on 2006 April 5th for 46 ks (see McLaughlin et al. 2007 for details on the analysis). In this observation we discovered

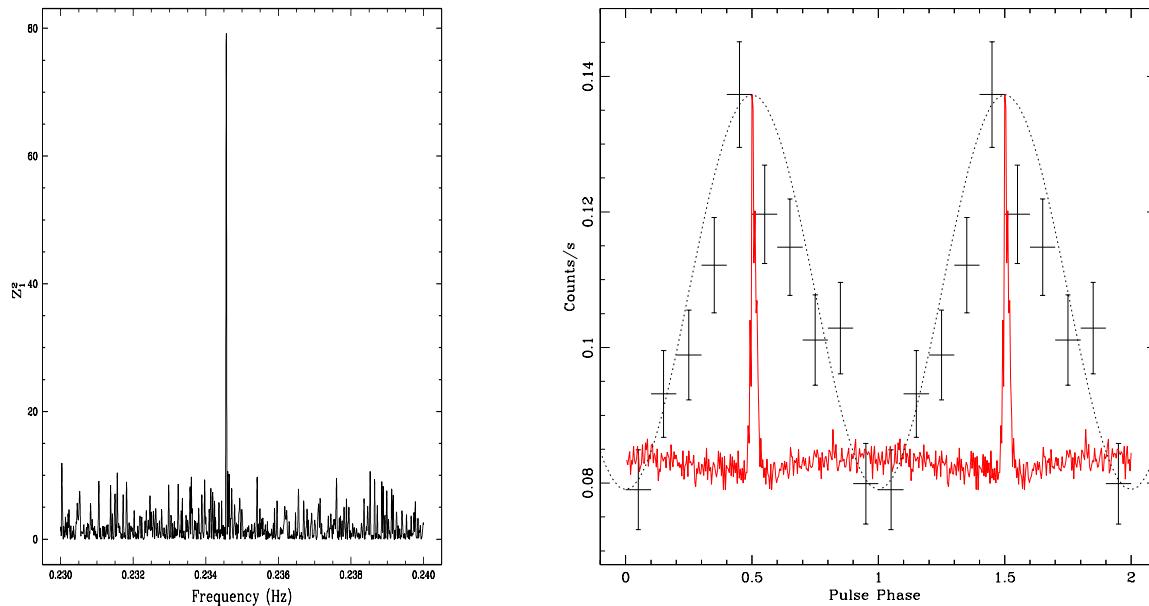


FIGURE 1. *Left panel:* Z-squared probability of the X-ray period search. *Right panel:* X-ray pulse profile (0.3–5 keV) for RRAT J1819–1458. Dotted line shows the best-fit sinusoid. Radio profile formed from 114 pulses detected in 6 hr of observation at 1.4 GHz with the Parkes telescope in Australia is over-plotted. Both profiles have been folded using the radio ephemeris. In both plots, two cycles of pulse phase are shown.

X-ray pulsations (see Fig. 1 left for a Z-squared plot) and intriguing absorption features in the X-ray spectrum (McLaughlin et al. 2007). This is the first detection of X-ray pulsations from any of the RRAT sources. The X-ray pulsations were discovered at the same periodicity derived from timing the arrival times of the radio bursts, confirming the neutron star nature of these objects as well as the technique used to time the radio bursts (McLaughlin et al. 2006).

In Fig. 1 (right), we present the X-ray profile over-imposed to the radio observations of the bursts folded with the same ephemeris: the radio bursts occurs exactly at the peak of the X-ray profile! The X-ray pulse profile has a 0.3–5 keV pulsed fraction of $34 \pm 6\%$ and can be well modeled as a single sinusoid, though there is a hint of additional structure that more sensitive observations may reveal. We found no hint for a dependence of pulsed fraction on energy, although our counts were not sufficient to significantly answer this point. We found no evidence for any X-ray bursts or aperiodic variability on any timescale.

The X-ray spectrum of RRAT J1819–1458 showed even more surprises: a single blackbody component did not fit the data because of the presence of two strong features around 0.5 and 1 keV (see Fig. 2 left). We checked whether these might be due to calibration issues, to our source and background extraction regions or to residual particle flares and/or particles hitting the detector, and could reliably exclude all of these. We tentatively concluded that the 0.5-keV line was not due to the source while to the

Oxygen edge, hence we modeled the spectrum excluding the 0.5–0.53 keV energy range, but more sensitive observations are necessary to confirm this. Several models give satisfactory results (giving our limited number of counts; see Tab. 2 in McLaughlin et al. 2007 for details): we show in Fig. 2 (right) the blackbody ($kT=0.14$ keV) plus a Gaussian ($E_G=1.1$ keV) fit. From Monte Carlo simulations (see Rea et al. 2005, 2007a) we infer the significance of the ~ 1 keV line to be 4σ . We tried to perform a pulse phase spectroscopy dividing the observation in 2 phase intervals, but the limited number of counts did not allow us neither to find significant spectral variability nor to give a strong constrain on that. Furthermore, we found a hint for an additional non-thermal component with $\Gamma \sim 1$, dominating the spectrum above 1.7 keV, however, the addition of a further component was not statistical significant given our number of counts, and the high background dominating above 2 keV did not allow us to disentangle this issue.

The two main interpretations for the 1 keV line is an atomic or cyclotron line. An atomic line could be due to the NS atmosphere or, less probably, to a peculiar abundance in the ISM in the direction of RRAT J1819–1458. The structure which remains in the residuals after fitting the broad line (see Fig. 2 right), which in our data is not statistically significant though, might be due to a blending of narrow lines which are unresolved due to limited counts. In the case of the feature due to proton cyclotron resonant scattering, the magnetic field inferred would be 2×10^{14} G, broadly consistent with that derived through radio timing of the bursts. In addition, the width and depth of the line are consistent with predictions for proton-cyclotron absorption in highly magnetized neutron stars (Zane et al. 2001). It is possible, although unlikely, that the feature is the first cyclotron harmonic, with the 0.5 keV fundamental coincident with the depression in the spectrum that we have interpreted as due to a mismodeling of the Oxygen edge. More counts are needed to differentiate between these scenarios. Moreover, pulse phase spectroscopy analysis is crucial for differentiating between the atomic and cyclotron models, with phase variation expected in the cyclotron hypothesis. If the feature we detect is indeed due to proton-cyclotron absorption, it provides an invaluable means of testing the assumptions implicit in characteristic magnetic fields derived through radio timing and an extremely valuable independent measurement of the magnetic field of an isolated NS. We will soon study these issues with a longer *XMM-Newton* observation.

RRAT J1317–5759

We observed RRAT J1317–5759 with *XMM-Newton* on 2006 July 16th, for a net exposure time of 30 ks. Data have been analysed following the same procedures and softwares used in Rea et al. (2007b). We find no X-ray counterpart for this RRAT with an upper limit on the PN Small Window counts of <0.012 , which translates in an absorbed 0.3–5 keV flux of $< 2.6 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$, assuming an absorption (derived from the source DM; Cordes & Shannon 2002) of $N_H = 5 \times 10^{21} \text{ cm}^{-2}$ and a blackbody spectrum with $kT=0.13$ keV (see Tab. 1 for the corresponding unabsorbed luminosity limit as well as for the distance used).

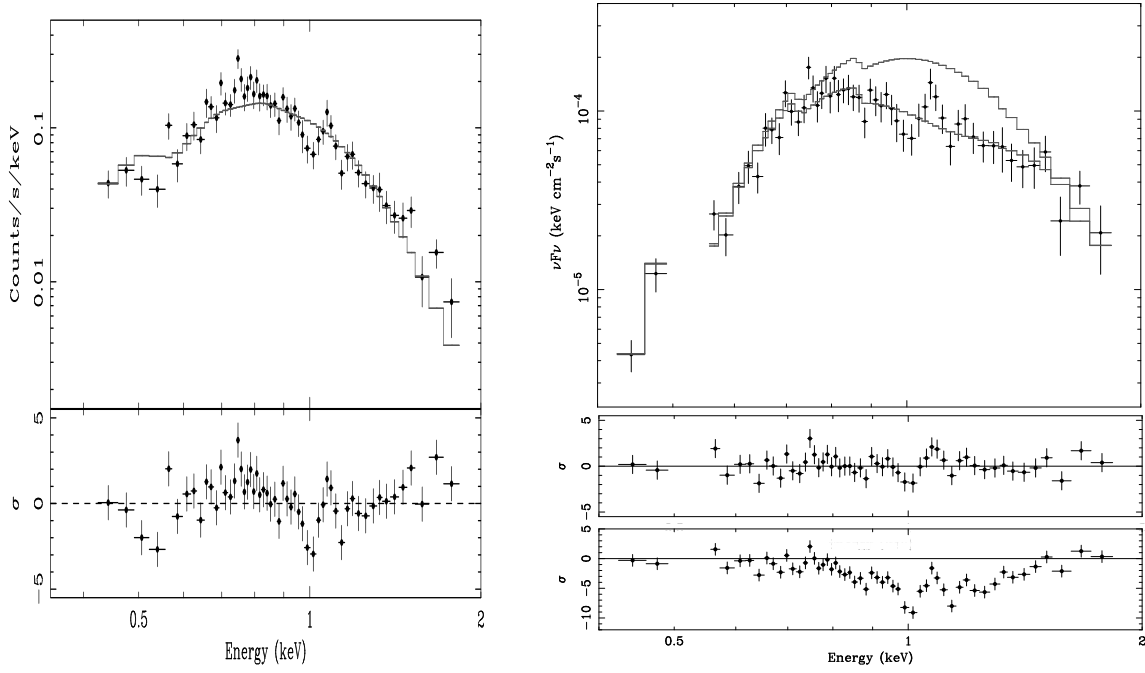


FIGURE 2. *Left panel:* *XMM-Newton* EPIC-PN spectrum of RRAT J1819–1458 modeled with an absorbed blackbody. *Right panel:* Top: *XMM-Newton* EPIC-PN νF_ν spectrum of RRAT J1819–1458, modeled with an absorbed blackbody and Gaussian line (see text). Top line shows the absorbed blackbody model alone. Middle: Residuals of the absorbed blackbody and Gaussian line model. Bottom: Residuals of the model without the inclusion of the Gaussian line.

RRAT J1913+1333

This RRAT has been observed with *Swift*-XRT on 2005 November 20th for an exposure time of 9.3 ks. Data have been analysed as reported in Rea et al. (2007c). Also in this case we find no X-ray counterpart for this RRAT with an upper limit on the *Swift*-XRT Photon Counting rate of <0.036 counts/s, which translates in an absorbed 0.3–5 keV flux of $<7.6 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$, assuming an absorption of $N_H = 8 \times 10^{21} \text{ cm}^{-2}$ (again derived from the source DM; Cordes & Lazio 2002) and a blackbody spectrum with $kT=0.13$ keV (see Tab. 1 for the corresponding unabsorbed luminosity limit as well as for the distance used).

DISCUSSION

We presented in this review new X-ray observations of three RRATs, RRAT J1819–1458, RRAT J1317–5759, and RRAT J1913+1333, showing that only for the first one there is a robust detection (see Tab. 1; Reynolds et al. 2006; McLaughlin et al. 2007). However, present upper limits, especially in the case of RRAT J1913+1333, are not very constraining, and deeper X-ray observations are needed.

Our detection of X-ray periodicity at the radio period of RRAT J1819–1458 shows that the X-ray source we previously reported in Reynolds et al. (2006) is undoubtedly

RRAT's X-ray counterpart. The pulsed fraction and sinusoidal pulse shape are similar to what is observed for other middle-aged X-ray detected radio pulsars such as PSR B0656+14 (e.g. De Luca et al. 2005), which moreover has been observed to have similar radio properties to the RRATs (Weltevrede et al. 2006).

The thermal emission from RRAT J1819–1458 is consistent with a cooling neutron star. However, the temperature from our blackbody fit ($kT \sim 0.14$ keV) appears slightly higher than temperatures derived from blackbody fits for other neutron stars of similar ages (see discussion by Reynolds et al. 2006). Note that it is possible that RRAT J1819–1458 was born spinning at a sizable fraction of its present period of 4.26 s. In this case, as discussed by Reynolds et al. (2006), its characteristic age of 117 kyr could be a considerable overestimate, and the inferred temperature could be completely consistent with its age. Note that characteristic ages have been shown to be misleading for several other pulsars (e.g. Gaensler & Frail 2000; Kramer et al. 2003).

Including RRAT J1819–1458, five over eight high-magnetic field radio pulsars have now been detected at X-ray energies. In particular, two of them, PSR J1846–0258 and PSR B1509–58, are bright non-thermal sources, as expected given their young ages (less than 2 yr). PSR J1119–6127 is a bright thermal X-ray emitter with unusual properties including a large pulsed fraction and narrow pulse (Gonzalez et al. 2005). PSR J1718–3718, with magnetic field of 7×10^{13} G, has been detected at X-ray energies, but the faintness of the counterpart does not allow detailed spectral modeling or a constraining limit on pulsed fraction (Kaspi & McLaughlin 2005). No X-ray emission has been detected from the other high-B pulsars PSR J1814–1744, PSR B0154+61 or PSR J1847–0130, the latter has the highest inferred surface dipole magnetic field (9×10^{13} G) measured to date for any radio pulsar (McLaughlin et al. 2003). Radio pulsar X-ray emission properties vary widely, even for objects with very similar spin-down properties. Of course, also the radio emission properties of RRAT J1819–1458 are quite different from the radio emission properties of these other high-B pulsars.

While the spectrum and luminosity of RRAT J1819–1458 argue against a relationship with magnetars, the recent detection of radio pulsations from the transient magnetar XTE J1810–197 (Camilo et al. 2006) raises the interesting possibility that RRAT J1819–1458 could be a transition object between the pulsar and magnetar source classes. The soft X-ray spectrum does have a comparable temperature to the quiescent state of XTE J1810–197 ($kT \sim 0.15 - 0.18$ keV; Ibrahim et al. 2004; Gotthelf et al. 2004). However, the radio emission characteristics of these two neutron stars are quite different. Would be very interesting to search for RRAT-like bursts from this transient magnetar when it will reach again the quiescent level.

While resonant cyclotron features are regularly observed from X-ray binary systems (e.g. Truemper et al. 1978; Nakajima et al. 2006), the detection of such features from isolated neutron stars is quite unusual. Bignami et al. (2003) discovered two (maybe four; see also Mori et al. 2005) harmonically spaced absorption lines from 1E 1207.4–5209, a radio-quiet X-ray pulsar with a 424-ms spin period and timing-derived characteristic age and inferred surface dipole magnetic field strength of 3×10^5 yr and 3×10^{12} G, respectively.

Broad absorption lines, similar to those seen for RRAT J1819–1458, have been observed for six out of seven XDINS (van Kerkwijk & Kaplan 2007; Haberl 2007). For most of these neutron stars, the lines can be interpreted as due to neutral hydrogen tran-

sitions in highly magnetized atmospheres. Van Kerkwijk & Kaplan (2007) argue that the transition energy is similar to the proton cyclotron energy for magnetic fields of the order of a few 10^{13} G. The X-ray spectrum of RRAT J1819–1458 is very similar (although with a slightly hotter blackbody temperature) to the XDINSs, although so far no convincing evidence for radio bursts have been detected for any of those thermally emitting neutron stars (Kondratiev et al. 2007 in prep.; Burgay et al. 2007 in prep.; Rea et al. 2007d).

One outstanding question is why absorption lines of this kind, whether due to the atmosphere or to cyclotron resonant scattering, have been observed from only a handful of X-ray emitting isolated neutron stars. The age of the neutron star could be one key factor. Young objects are dominated by non-thermal emission, but older ones may be too faint for X-rays to be detectable, making X-ray bright, middle-aged pulsars the best candidates (as is the case of the XDINSs and of RRAT J1819–1458). Note, however, that no such absorption lines have been found for the X-ray bright, middle-aged PSR B0656+14, despite deep searches both with *Chandra* (Marshall & Schultz 2002) and *XMM-Newton* (De Luca et al. 2005). Another factor might well be the viewing angle.

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